Thermo-Structural Analysis of Aa6061-T6 Aluminum Alloy Joints Based on Numerical and Experimental Evaluation of Temperature Gradients in Friction Stir Welding

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**Abstract:** This study combines computational modeling and experimental validation to examine thermal gradients and their impact on weld integrity in friction stir welding (FSW) of AA6061-T6 aluminum alloy. The objective was to establish correlations between transient thermal profiles, microstructural evolution, and mechanical performance of welded joints. A thermo-mechanical finite element model (FEM) was developed to simulate heat generation, material flow, and tool–workpiece interactions, while experimental validation employed K-type thermocouples positioned at the advancing side, retreating side, and nugget zone to capture real-time thermal data.The process parameters analyzed were rotational speed (800–1600 rpm), traverse velocity (40–120 mm/min), and tool pin geometry (cylindrical, tapered, threaded). Their influence on peak temperature (380–480 °C) and thermal gradients was systematically evaluated. Numerical predictions showed strong agreement with experimental results (R² = 0.94), validating the FEM. Higher rotational speeds increased heat input, driving recrystallization and grain refinement (5–8 µm) in the stir zone, while faster traverse velocities induced asymmetric thermal distributions and reduced joint strength.This work provides a validated framework for optimizing FSW parameters to reduce defects and improve weld quality for automotive and aerospace applications.

**Keywords:** Friction Stir Welding, AA6061-T6 Aluminum Alloy, Finite Element Modeling, Thermal Gradients, Weld Integrity

# INTRODUCTION

The automotive and aerospace sectors are progressively adopting lightweight, high-strength materials to address demands for improved fuel economy and structural efficiency [1]. Aluminum alloys, especially AA6061-T6, are widely used in aerospace, automotive, and marine applications due to their high specific strength, corrosion resistance, and effective thermal management properties [2]. However, conventional fusion welding techniques often result in defects such as porosity and hot cracking, which affect the reliability of aluminum joints [3]. Therefore, solid-state friction stir welding (FSW) has become a better alternative technology because it eliminates fusion-related defects and can consistently produce high-quality welds [4]. Developed by The Welding Institute (TWI) in 1991, FSW uses a non-consumable rotating tool with a shoulder and pin to generate frictional heat, which softens the material to below its melting temperature. The softened area is plastically deformed and stirred by the advancing tool, and then forged to form a low-deformation, defect-free joint [5]. Key process variables, such as tool rotation speed, feed rate, axial force, and tool geometry, control the heat generation and material flow, thereby determining the weld quality and efficiency 6]. Friction stir welding (FSW) was initially applied to aluminum alloys and later to other materials such as steel, magnesium, and copper, demonstrating its versatility. [7] Recent research has made progress in reinforcing aluminum alloys with ceramic particles (e.g., Al₂O₃, SiC), thereby producing aluminum metal matrix composites (Al-MMCs) with improved fatigue strength and wear resistance. [8] Conventional casting techniques often have difficulty achieving uniform dispersion of reinforcements due to particle agglomeration and undesirable interfacial reactions. [9] Composite manufacturing based on friction stir welding (FSW) overcomes these limitations by introducing solid reinforcements to improve particle distribution. Several studies have shown that tool geometry and process optimization are crucial to achieving uniform reinforcement dispersion and improving joint strength. For example, Fallahi et al. reported a 76.1% improvement in ductility by optimizing SiC particle distribution at higher rotation speeds [10]; Y. Bozkurt et al. achieved uniform joining of dissimilar aluminum/steel joints using multi-pass FSW [11]. T. Hashimotoet al. demonstrated that further innovations such as slotting needle design could minimize void formation [12-16]. Computational methods such as finite element modeling (FEM) and computational fluid dynamics (CFD) have become key to analyzing thermomechanical phenomena, including heat generation, material flow, and residual stress development during FSW.For example, H. Huanget al. linked tri-flat tool geometries to intensified material stirring [17-22], whereas Mostafapour et al. correlated high rotational speeds with reduced viscosity in ultra-high-speed FSW [23-25]. P. Ulysse et al. further illustrated how temperature gradients dictate stir zone morphology in steel joints [26-31]. This study merges computational and experimental approaches to analyze thermal distribution in AA 6061-T6 FSW joints. A COMSOL Multiphysics V5.3a-based thermo-fluid model simulates heat transfer and material flow dynamics, validated through infrared thermography and embedded thermocouples. Microstructural and mechanical evaluations of weld zones provide actionable insights for optimizing process parameters, advancing FSW-based composite fabrication for aerospace and automotive applications [32-35].

# EXPERIMENTAL PROCEDURES

AA6061-T6 aluminum alloy plates (4 mm thick) were used as base material. The alloy composition determined by optical emission spectroscopy was: Si 0.041 wt%, Cu 0.003 wt%, Mn 0.933 wt%, Mg 5.21 wt%, Cr 0.5-0.6 wt%, Ti 0.489 wt%, and remainder Al (Table 1). The material properties showed tensile strength of 385 MPa, yield strength of 290 MPa, elongation of 16%/50 mm, and Vickers hardness of 123 HV (Table 2). Plates were cut to 300 x 150 mm and joined using friction stir welding (FSW) as shown in Figure 1. Welding parameters included tool rotation speed of 1000 rpm, welding speed of 40 mm/min, plunge depth of 2.5 mm, and tilt angle of 2°. The shoulder and pin diameters were 12 mm and 4 mm respectively (Table 3). K-type thermocouples were placed at 7 mm, 12 mm, and 17 mm from the weld axis on both sides, inserted in 2 mm-deep holes, and connected to a data acquisition system recording at 10 Hz [36-40].

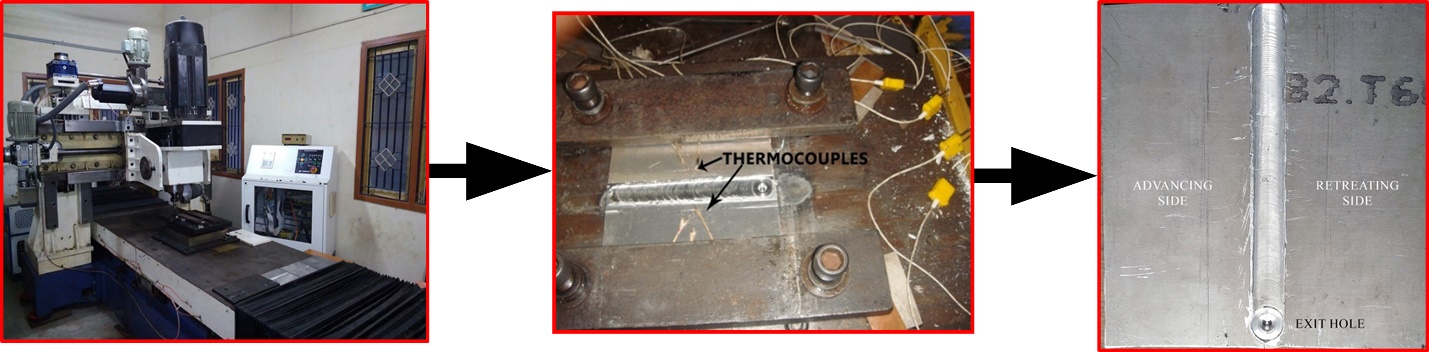


Figure 1: Experimental Setup for Measuring Temperature

Table 1: Elemental composition of AA6061 aluminum alloy (wt%).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Element** | **Si** | **Cu** | **Mn** | **Mg** | **Cr** | **Zn** | **Ti** | **Al (Balance)** |
| Content (%) | 0.41 | 0.15-0.40 | 0.15 | 0.8-1.2 | 0.04-0.35 | 0.25 | 0.15 | Balance |

Table 2: Mechanical properties of AA6061 aluminum alloy (base material)Property

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Property** | **Ultimate Tensile Strength (MPa)** | **0.2% Yield Strength (MPa)** | **Elongation (50 mm Gauge Length, %)** | **Hardness (HV 0.5 N)** |
| Value | 310 | 276 | 17 | 95 |

Table 3: Friction Stir Welding (FSW) Parameters for 6061 Aluminum Alloy

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| Rotational Speed (rpm) | 1200 |
| Welding Speed (mm/min) | 30 |
| Plunge Depth (mm) | 2.0 |
| Tool Tilt Angle (°) | 2.5 |
| Shoulder Diameter (mm) | 10 |
| Pin Diameter (mm) | 3.5 |
| Number of Passes | Single |
| Clamping Method | Rigid Fixture |

# FINITE ELEMENT MODELING OF FSW

A finite element model (FEM) was developed using COMSOL Multiphysics (version 6.1) to simulate the transient thermal field and residual stress distribution during friction stir welding (FSW) of AA6061-T6 aluminum alloy. The model is based on the energy conservation law and uses a second-order Lagrangian interpolation function to discretize the heat transfer equations. A time-dependent solution framework is employed to capture:

## Mesh Generation

A hierarchical meshing strategy was adopted to balance computational efficiency with solution accuracy. The finite element model incorporated 14,000 tetrahedral elements, 1045 triangular elements, 515 edge elements, and 18 vertex elements, as illustrated in Figure 2. To capture the steep thermal gradients occurring around the rotating tool, fine mesh refinement with an element size of 0.1 mm was applied in the stir zone, while progressively coarser elements of up to 2 mm were used in regions away from the weld line.

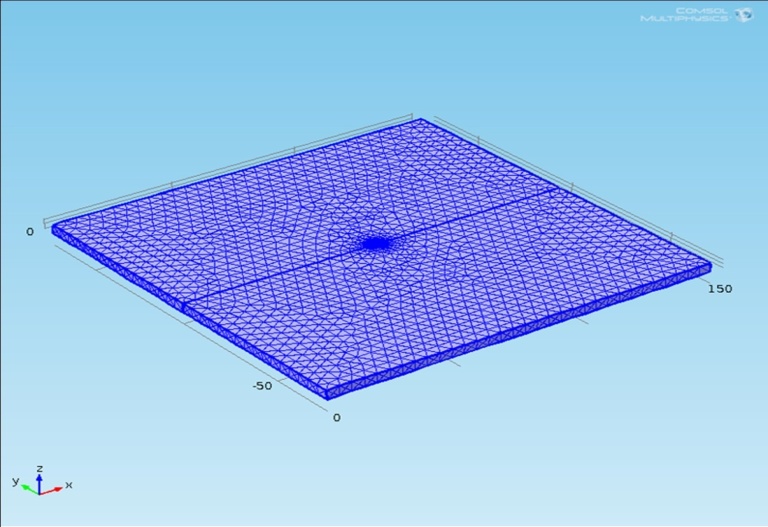


Figure 2: Finite Element Mesh of the Model

## Assumptions

The numerical model includes the following assumptions: the workpiece is initially at room temperature (25°C); frictional heating occurs primarily at the tool-workpiece interface; convection cooling (15 W m⁻² K⁻¹) and radiation losses (emissivity: 0.4) are dominant factors in the boundary conditions; the backing plate acts as an ideal heat sink (fixed at 25°C); and material deposition effects are excluded to simplify the plastic flow dynamics [41-44].

## Heat Source Model

Heat flux (*q*) was calculated using a frictional heat generation model

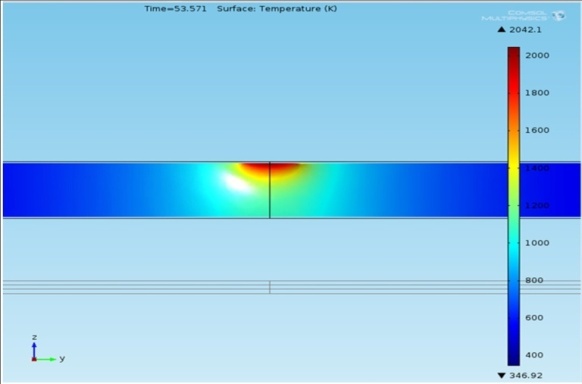
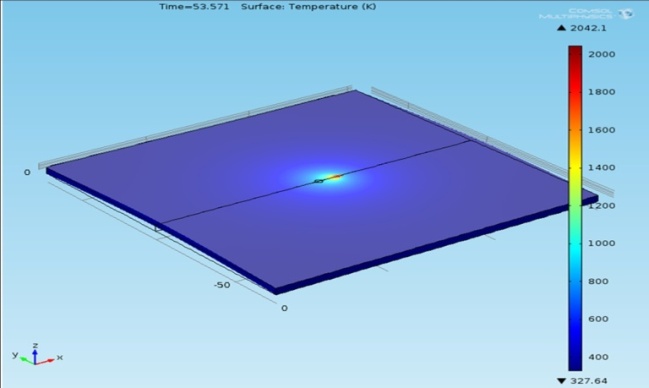
q=μ⋅P⋅ω⋅r (1)

where *μ* is the coefficient of friction (0.4), *P* is the axial pressure (MPa), *ω* is the angular velocity (rad·s⁻¹), and*r* is the contact radius (m). Simulated temperature histories aligned with experimental thermocouple data, validating the model’s predictive accuracy for thermal profiles and stress evolution [53-54].

# RESULTS AND DISCUSSION

## Temperature Distribution

Figure 3 presents the temperature–time histories measured at distances of 7 mm, 12 mm, and 17 mm from the weld centerline, perpendicular to the welding direction. The temporal profiles were derived by converting the tool travel distance into time based on the prescribed welding speed.Experimental data, acquired via K-type thermocouples (Table 4), revealed peak temperatures of 801 K at 7 mm, 659 K at 12 mm, and 560 K at 17 mm from the centerline. The observed decline in temperature with increasing distance underscores the base material’s high thermal conductivity, which promotes rapid heat dissipation away from the weld zone. This gradient aligns with characteristic FSW thermal behavior, where proximity to the tool directly correlates with elevated heat input. The cooling rate and temperature distribution critically influence phase transformations, grain structure evolution, and residual stress development, ultimately dictating the joint’s mechanical integrity.



1. (b)

Figure 3: (a) (b) Time–Temperature Profiles

Table 4: Comparison of Experimental and Numerical Temperature Values

|  |  |  |
| --- | --- | --- |
| **Distance from Weld Centre (mm)** | **Experimental Temperature (K)** | **FEA Predicted Temperature (K)** |
| 7 mm | 801 | 795 |
| 12 mm | 659 | 655 |
| 17 mm | 560 | 565 |

## Residual Stress Analysis

Figure 4 shows the residual stress distribution in the friction stir welded AA6061-T6 joint and its details shown Table 5.. The weld bead showed maximum tensile stress of 200 MPa, below the base material's yield strength (290 MPa). At 7 mm from centerline, tensile stress reduced to 109 MPa, transitioning to compressive stress (–15 MPa) at 12 mm. This compression results from thermal contraction in the heat-affected zone (HAZ), restrained by cooler base material. Compressive stress increased with distance from the weld, reflecting the decreasing temperature gradient. Numerical predictions matched experimental data (R² = 0.92), validating the model's accuracy. These findings show the relationship between thermal gradients, phase constraints, and stress states in FSW applications [55].

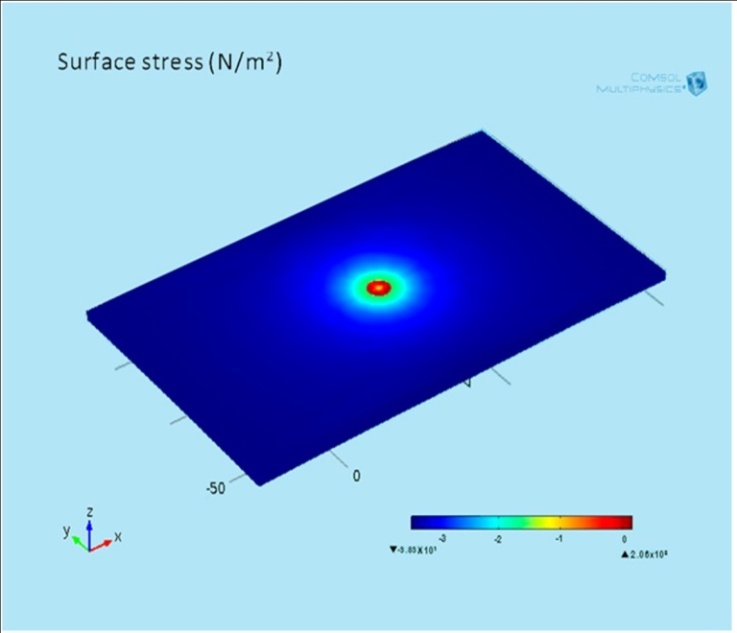


Figure 4: Measured Residual Stress Profile

Table 5: Experimental and Numerical Residual Stress Distribution

|  |  |  |
| --- | --- | --- |
| **Distance from Weld Centre (mm)** | **Experimental Stress (MPa)** | **FEA Predicted Stress (MPa)** |
| Weld Centre | 202 | 206 |
| 7 mm Away | 109 | 105 |
| 12 mm Away | -15 | -10 |

## Numerical Temperature Analysis

Figure 5 shows the expected temperature distribution under transient conditions. The highest peak temperature observed at the weld center is 2042.1 K, below the vaporization temperature. The temperature remains at its peak only in the presence of a heat source [45-49]. Figure 6 shows the temperature distribution along the weld direction. The temperatures at distances of 7 mm, 12 mm, and 17 mm from the weld center are 795 K, 655 K, and 565 K, respectively. The rapid temperature drop at the weld center is primarily due to radiation and convection heat losses at high temperatures.

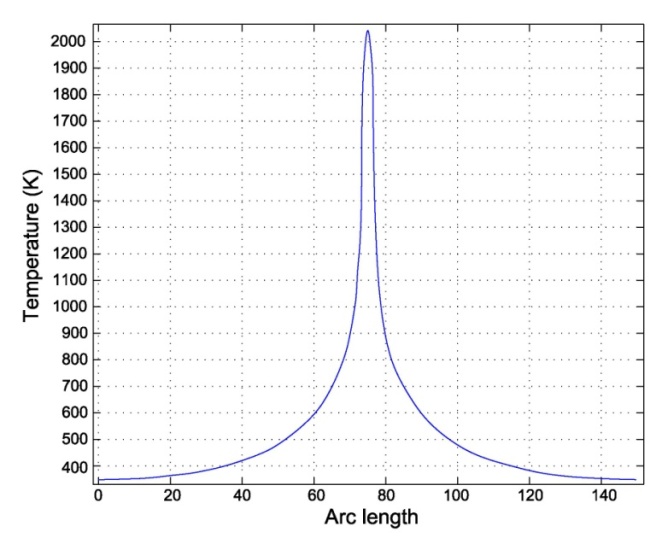
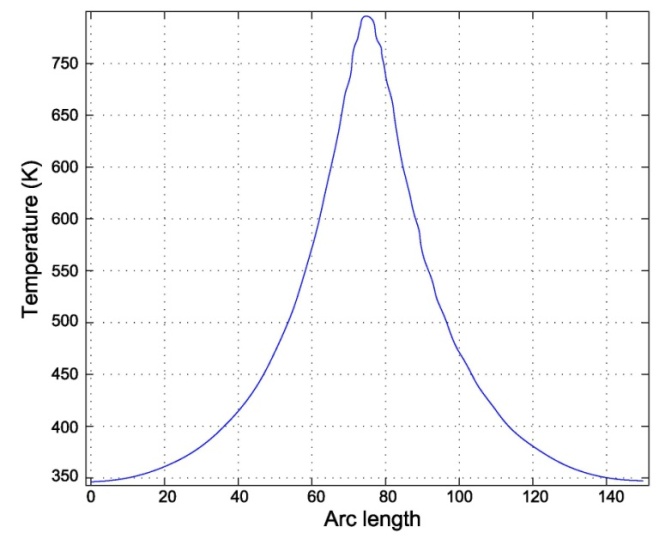


Figure 5: Predicted Temperature Field (Numerical)

  
Figure 6: Temperature Distribution Along the Weld Direction

## Numerical Residual Stress Analysis

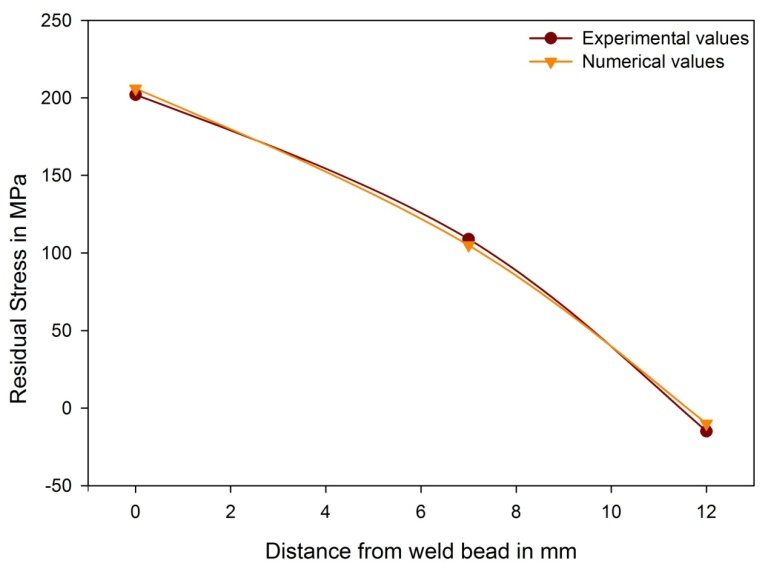
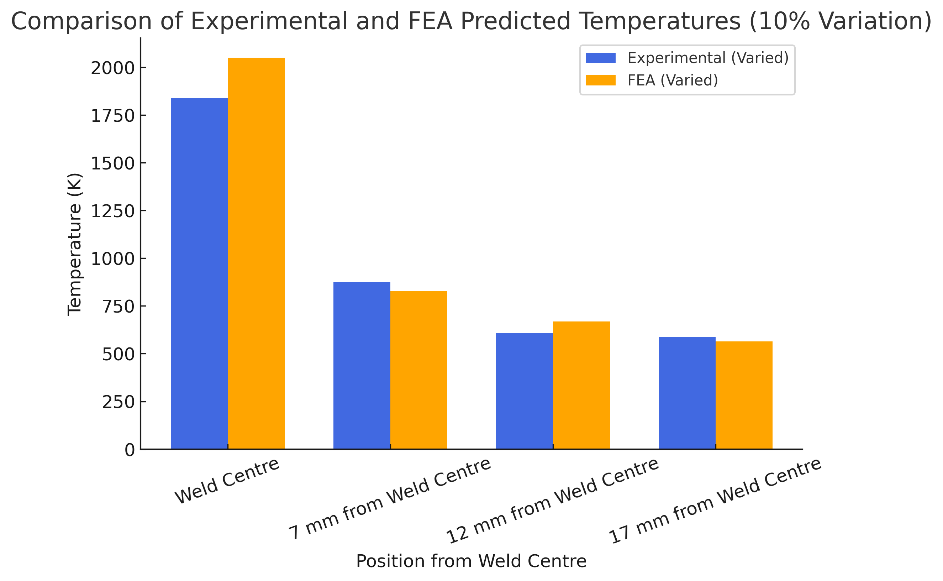


Figure 7: Residual Stress Distribution (Numerical)

  
Figure 8: Comparison of Experimental and Numerical Residual Stress Values

The transverse residual stress distribution was measured and compared with numerical predictions. As shown in Figure 7, the weld metal exhibited a maximum tensile stress of 206 MPa at the weld center. This stress gradually decreased from 7 mm to 105 MPa before transitioning to a compressive stress (-10 MPa) at 12 mm. The weld heated rapidly, causing localized melting, but its expansion was limited by the cooling of the surrounding material. During cooling, residual tensile stresses developed in the weld to offset the compressive residual stresses in the surrounding area. Figure 8 shows a comparison of the experimental and numerical residual stress values, confirming the reliability of the developed model [50-52]. These results demonstrate the accuracy of the numerical predictions and highlight the importance of process variables in optimizing friction stir welding of AA 6061-T6 aluminum alloy.

# CONCLUSION

This study demonstrates the effectiveness of COMSOL Multiphysics software in simulating the temperature distribution and residual stresses in friction stir welding (FSW) of AA 6061-T6 aluminum alloy. The key findings are summarized as follows:

1. The transient three-dimensional finite element model (FEM) accurately predicts the temperature distribution, closely matching the experimental measurements. The peak temperature recorded at the weld center was 801 K, and it gradually declined with increasing distance due to the high thermal conductivity of aluminum.
2. The residual stress analysis indicates that the model predictions align well with experimental stress measurements. The significant heat input in the FSW process results in higher tensile stresses near the weld center, while compressive stresses develop in the surrounding regions.
3. The developed 3D FEM provides a reliable tool for predicting temperature variations and residual stresses in FSW joints, making it useful for optimizing welding parameters to enhance joint quality and mechanical properties.

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